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Analysis of magnetic flux in magneto-rheological damper

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¹ Author to whom any correspondence should be addressed.E-mail: sjpurand@iupui.edu and arazban@iupui.edu**Keywords:** magneto-rheological fluid, magneto-rheological damper, finite element analysis, magnetic circuit, magnetic flux density, magnetic flux intensity**Abstract**

Magnetorheological materials are a class of smart substances whose rheological properties can rapidly be varied by application of a magnetic field. The proposed damper consists of an electromagnet and a piston immersed in MR fluid. When current is applied to the electromagnet, the MR fluid solidifies as its yield stress varies in response to the applied magnetic field. Hence, the generation of a magnetic field is an important phenomenon in MR damper. In this research, the magnetic field generated in the damper was analyzed by applying finite element method using COMSOL Multiphysics and was validated using magnetic circuit theory. A quasi-static, 2D—Axisymmetric model was developed using parametric study by varying current from 0–3 A and the magnetic flux density change generated in the fluid flow gap of MR fluid due to external applied current was evaluated. According to the analytical calculations magnetic flux density generated at MR fluid gap was 0.64 Tesla and when calculated using FEA magnetic flux density generated was 0.61 Tesla for 1A current. There is a difference of 4.8% in the simulated results and analytically calculated results of automotive MR damper due to non linear BH curve consideration in Finite element analysis over linear consideration of BH relation in magnetic circuit theory.

Nomenclature

A	Vector potential field
A _i	Area of the rings
B	Magnetic flux density
g	Fluid gap
H	Magnetic flux intensity
I	Current applied to the coil
J _e	Current density
L _i	Length of the links
L _p	Pole length
L	Piston length
MR	Magneto Rheological
MRF	Magneto Rheological Fluid
M _t	Magnetic Reluctance
N	Number of turns of coil
R	Outer radius of the Piston
R _c	Inner radius of the piston
t	Cylinder wall thickness

W_c	Coil width
$\dot{\gamma}$	Shear strain rate
μ_0	Relative permeability of vacuum
μ_p	Apparent viscosity of the fluid
τ	Shear stress of the fluid
τ_y	Yield stress of the fluid
σ	Electrical conductivity
ϕ	Magnetic Flux

1. Introduction

One of the most recent and promising technologies in vehicle damper design is implementing Magnetorheological (MR) fluids. These smart fluids have the capability to continuously and rapidly change their rheological behavior (viscosity) under applied magnetic field [1, 2]. Due to these unique characteristics, MR based dampers can provide variable damping force semi-actively by varying the applied magnetic field (varying current), thus they have the capability to control vibration in a wide range of road conditions. Magnetorheological fluid (MRF) consists of a suspension of microscopic magnetizable particles in a non-magnetic carrier medium, the fluid behaves in a Newtonian manner (figure 1(a)) [3]. Applying a magnetic field causes the microscopic particles suspended in the fluid to become uniformly oriented and form chains along the magnetic flux lines (figure 1(b)) [3]. This temporary internal structure changes the fluids rheological behavior [4]. When flow occurs perpendicular to the magnetic flux lines, the resistance of the micro particle chains causes the fluid to exhibit an yield stress that is not uniform. Thus, when a magnetic field is applied to an MRF in a fluid gap which has flux lines due to electromagnetic circuit, the fluid behaves similarly to a Bingham plastic [5].

Recently, some studies have focused on finite element analysis of the MR damper for calculating magnetic flux density and for geometric optimization. Parlak *et al* [6] has proposed design parameters based on the optimization method and used magnetostatics and CFD in the finite element analysis tool ANSYS to obtain optimal value of design parameters. Zhang *et al* [7] has proposed the use of finite elements to improve the magnetic design of an MR damper. Ferdaus *et al* [8] has established a 2D axi-symmetric and a 3D model of an MR damper that considered not only the shape of the piston, the MR fluid gap, the air gap but also the thickness of the damper's housing. Finite element method (FEM) has been also used in the modeling and design of MR valves and dampers [9]. Guo *et al* [10] has conducted finite element analysis of an MR valve using ANSYS and generated a magnetic circuit using a C shaped electromagnet. Khan *et al* [11] and Walid [9] has analyzed magnetic flux density in a 2D -axisymmetric model using ANSYS and derived results for four different piston designs before determining the best piston design for maximum flux density. Case *et al* [12] has conducted a Multiphysics Analysis of an MR damper for medical orthosis and then generated magnetic flux density in MR damper with applied current of 0 mA to 500 mA using COMSOL Multiphysics.

Previously ANSYS software had been used to model MR damper but MR fluid properties cannot be modeled accurately using ANSYS. Hence to model the MR Fluid accurately taking BH curves and variation of yield stress with respect to magnetic field into consideration, COMSOL multiphysics software was used in this research. Unlike the existing magnetostatic analysis, the new techniques of magnetostatics of MR damper and its validation using magnetic circuit theory are presented in this research.

2. Design and modeling of MR damper

Dissipation of energy via volume change is the basic operating principle of dampers. In conventional dampers dissipation of energy due to road disturbances is a function of volume flow rate change caused by damper piston orifice design and fluid viscosity. This operating principle means that the conventional damper is a constant energy dissipation damper. Magneto rheological dampers have the ability to change the viscosity of the fluid because of the magnetic excitation provided to operating fluid [13, 14]. Increasing excitation results in both increased magnetic flux through the fluid and an increased resistance to fluid flow, which ultimately results in increased dissipation of energy per cycle.

While all MR dampers operate on the same principle, their fabrication varies. Based on the principle of construction, used MR dampers are classified as either twin tube, mono tube, or double end dampers. Each type comes with its own advantages and disadvantages. Double ended MR damper consists of two piston rods protruding through both the end of dampers which is mostly suited for the impact applications. It does not

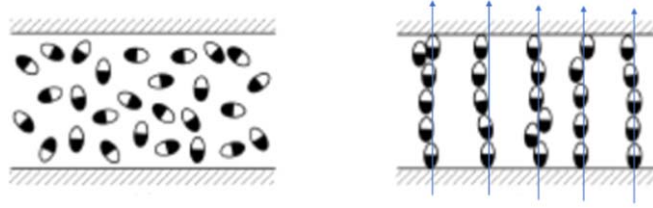


Figure 1. Example of particle orientation in the (a) absence and (b) presence of magnetic field in the fluid space [3].

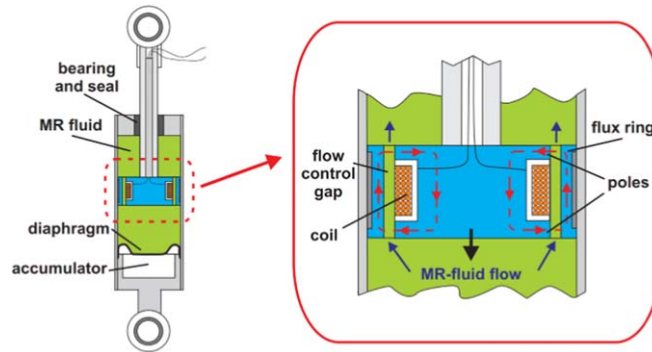


Figure 2. Design of monotube MR damper [18].

require an accumulator. These dampers have been used in gun recoil applications [15], bicycle applications [16]. Twin tube dampers are the easiest to manufacture and operate at the lowest pressures thus reducing the overall manufacturing and operation cost but it may cause cavitation since oil and gas chambers are not separated reducing the performance. Monotube dampers, on the other hand, operate at highest pressures resulting in lowest cavitation and most efficient operation of the damper. Although these dampers are expensive to manufacture but these are easy to install and smaller in size. Hence the best choice for an automotive damper per the construction consideration is monotube MR damper which was used in this study [17]. The basic design of a monotube MR is shown in figure 2.

The MR damper composes of a main damper housing, a piston and piston rod assembly, and an accumulator. The piston is wound by multi-turn coil which is the main source of magnetic flux. The piston rod, piston and cylinder are all analyzed using magnetic material through which current is passed to the coil making the electromagnetic circuit in the damper and creating magnetic flux [19]. The main reservoir contains the piston and piston rod assembly submerged in the MR fluid, while the accumulator reservoir contains a compressed, non-oxidizing gas (usually nitrogen). As the piston rod moves into the damper housing, a volume of fluid equivalent to the volume of the intruding piston rod is displaced through an annular gap of fluid. The accumulator piston then moves toward the bottom of the damper, compressing the nitrogen charge to account for the change in volume. As the piston rod retracts, the accumulator piston elevates the damper tube to counteract the loss of volume. 3D geometry of MR damper is generated using CREO software shown in figure 3.

3. Magnetic circuit theory

It is well-known that modeling MRF based systems is a multi-physics analysis problem: based on both electromagnetic analysis and fluid system analysis. To facilitate the depth of this research, electromagnetic analysis was the sole focus. The purpose of such modeling was to find the relation between the applied electric power (usually the current applied to the coils) and the output magnetic flux density and intensity which changes yield stress of the fluid. In order to accurately and effectively model an MR damper, first the magnetic circuit of this damper was calculated using Ampere's law stated in equation (1) [20]

$$\int H * dl = N * I \quad (1)$$

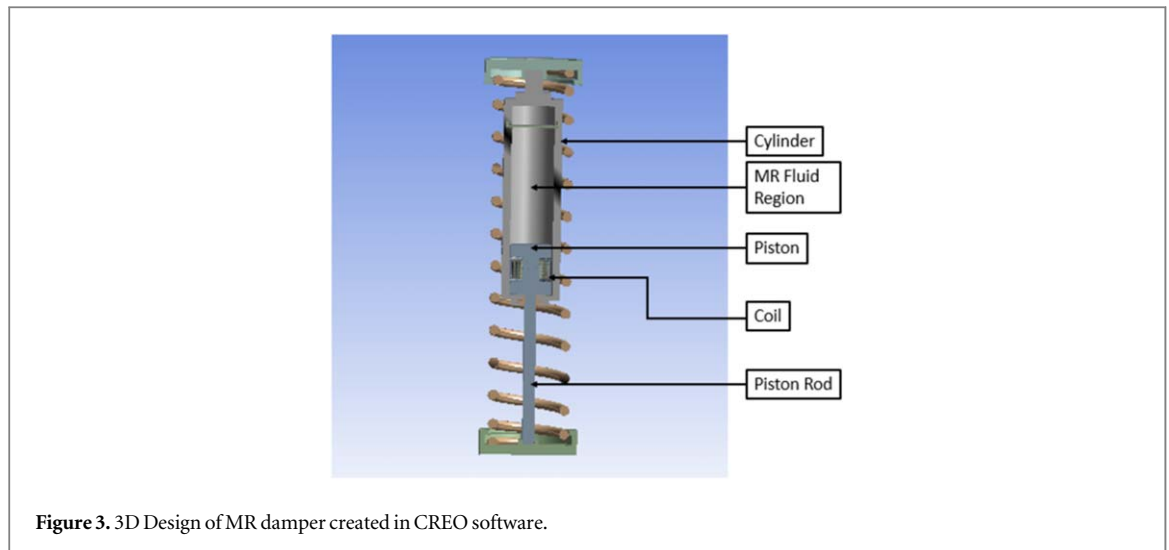


Figure 3. 3D Design of MR damper created in CREO software.

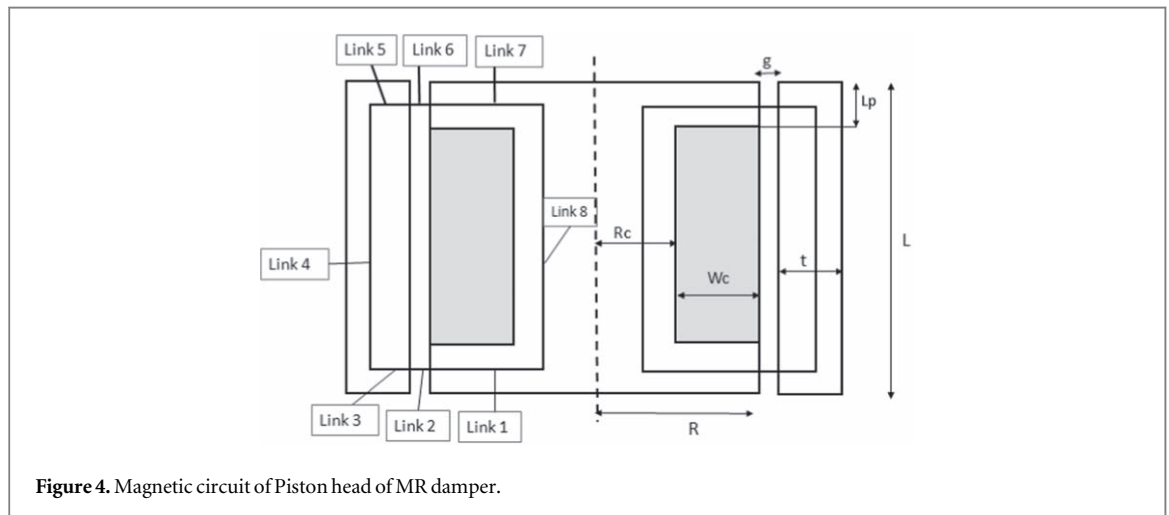


Figure 4. Magnetic circuit of Piston head of MR damper.

equation (1) is rewritten as given in equation (2)

$$\sum_{i=1}^8 H_i L_i = N * I \quad (2)$$

The piston head valve is shown in figure 4. Magnetic flux is generated because of the current and the number of turns of coil. The magnetic field causes magnetic flux to follow the path of least magnetic reluctance as shown in the figure 5. It shows the magnetic circuit in the piston head of the MR damper where magnetic flux is generated in piston head and MR fluid. Magnetic reluctance occurs in series and is represented by the following equation (3)

$$M_t = \sum_{i=1}^8 (L_i / \mu_i * A_i) \quad (3)$$

L_i is length of links as shown in figure 4, μ_i is relative permeability of material, $\mu_{2,6}$ is 5.5, $\mu_{1,3,5,7,8}$ [21] is 1600 of MR Fluid and Low carbon steel respectively.

Reluctance of circuit is based on length, permeability and area of the link. Magnetic reluctance and circuit is shown in figure 5. Thus, the greater the area and permeability of the link and less was the reluctance, the greater magnetic flux was generated in the circuit given in equation (4)

$$\phi = N * I / M_t \quad (4)$$

where ϕ is Magnetic Flux

Length of Links for the calculation of magnetic flux are given in equations (5)–(8) [22] which are shown in figure 4

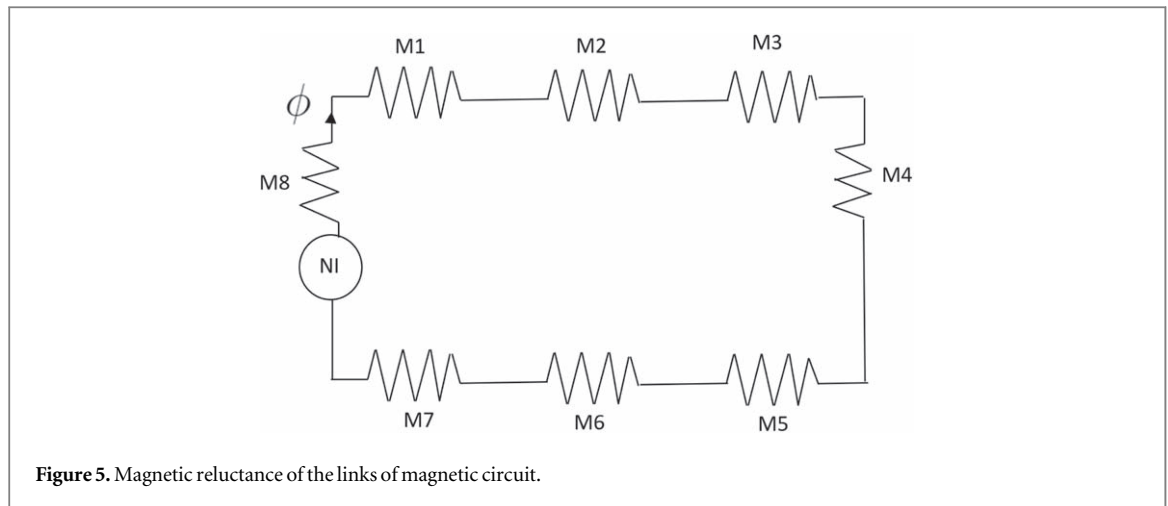


Table 1. Parameters used for calculation of magnetic flux.

Parameter	Expression	Value
Piston radius	R	21 mm
Piston internal radius	R _c	10 mm
Pole length	L _p	8 mm
Piston outer thickness	t	8 mm
Length of piston head	L	50 mm
Width of coil	W _c	10 mm
Fluid annular gap	g	1.3 mm

$$L_1 = L_7 = R - \frac{R_c}{2} \quad (5)$$

$$L_2 = L_6 = g \quad (6)$$

$$L_3 = L_5 = \frac{t}{2} \quad (7)$$

$$L_4 = L_8 = L - L_p \quad (8)$$

And cross sectional Areas of the links are given in equations (9)–(13)

$$A_1 = A_7 = 2 * \pi * L_p * \left[R - \frac{R_c}{4} \right] \quad (9)$$

$$A_2 = A_6 = 2 * \pi * L_p * \left[R + \frac{g}{2} \right] \quad (10)$$

$$A_3 = A_5 = 2 * \pi * L_p * \left[R + g + \frac{t}{4} \right] \quad (11)$$

$$A_4 = \pi * \left[(R + g + t)^2 - \left(R + g + \frac{t}{2} \right)^2 \right] \quad (12)$$

$$A_8 = \pi * (R_c)^2 \quad (13)$$

Parameters used for the calculation of magnetic flux using FEA and magnetic circuit theory are given in table 1. Using the above equations total magnetic reluctance in the circuit was calculated and magnetic flux density in MR fluid gap is given in equation (14)

$$B = \mu_0 * \phi / A_2 \quad (14)$$

Where μ_0 is relative permeability of vacuum - $4\pi * 10^{-7} \text{H/m}$

In a ferromagnetic material, magnetic flux density B represents the magnitude of the internal field strength within a substance that is subjected to an H field [23] given in equation (15)

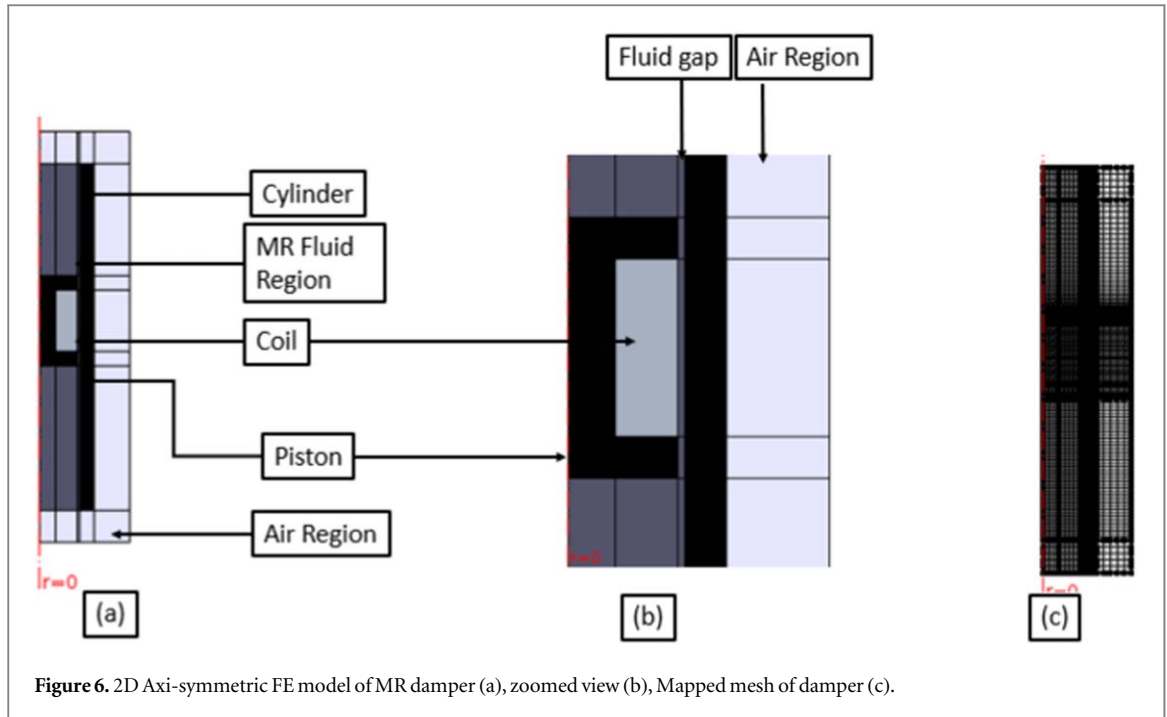


Figure 6. 2D Axis-symmetric FE model of MR damper (a), zoomed view (b), Mapped mesh of damper (c).

$$B = \mu_0 * \mu_r * H \quad (15)$$

Thus magnetic flux intensity can also be calculated using the above relation given in equation (15) in MR fluid gap. For analytical calculations this linear relationship of magnetization was used.

The magnetic circuit design which causes change in the yield stress of the MR fluid is one of the most important phenomenon since the rheology (viscosity) of the MR fluid is dependent on yield stress of the fluid. By applying the least-squares curve fitting method [24] to the fluid property specifications of MRF 132DG fluid the yield stress was determined by equation (16)

$$\tau_y = 52.962B^4 - 176.51B^3 + 158.79B^2 + 13.708B + 0.1442 \quad (16)$$

This yield stress and viscosity relation were explained using bingham plastic model, which is given in equations (17) and (18)

$$\tau = \tau_y(B) \operatorname{sgn}(\dot{\gamma}) + \mu_p \dot{\gamma} \quad (17)$$

When $\tau > \tau_y$ and

$$\dot{\gamma} = 0 \quad (18)$$

When $\tau < \tau_y$

Above equations states that the fluid acts as a rigid body when magnetic field is applied in the fluid gap below dynamic yield stress which is responsible for damping.

4. Finite element analysis

In the current research, commercial FEM tool COMSOL Multiphysics was used by adding a CFD module and an AC/DC module to analyze the magnetic circuit produced in the MR damper [25], since the non linear properties of MR fluid can be modeled accurately in COMSOL multiphysics. Because the geometry of damper structure was axisymmetric, to reduce the computational cost a 2-D axisymmetric model as shown in figures 6(a) and (b) was used to develop the finite element modeling of the damper for the purpose of electromagnetic analysis. The magnetic flux density (B) in the MR fluid under applied varying current of 0–3 Amp was determined using Ampere's law.

The Rectangular body was created around the damper which represents the air that acts as a magnetic insulator. 2D axisymmetric Geometry created in COMSOL is as shown in figures 6(a) and (b). Mapped mesh was generated as shown in figure 6(c). This model was tested to find the magnetic flux density generated in fluid gap due to current variation in electromagnetic coil. MR fluid used in this study was MRF 132DG because of the larger operating temperature range of fluid. The properties of the MR fluid are given in table 2 [26]. The non linear magnetic properties of MR fluid—BH curve shown in figure 7 and yield stress versus magnetic field intensity of this fluid are given by Lord Corporation shown in figure 8. Low carbon steel AISI 1018 is assigned to

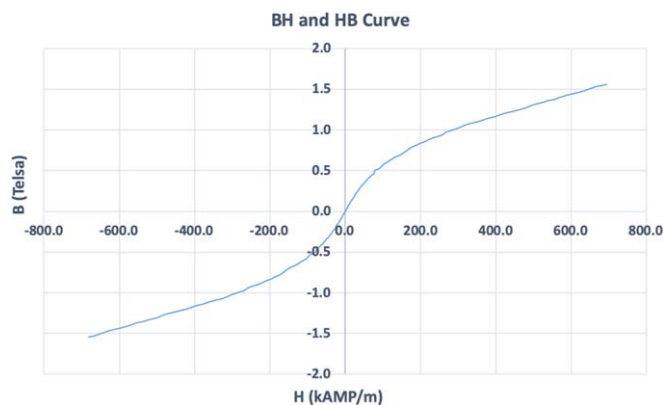


Figure 7. Typical magnetic properties of MRF 132DG by Lord corporation [28].

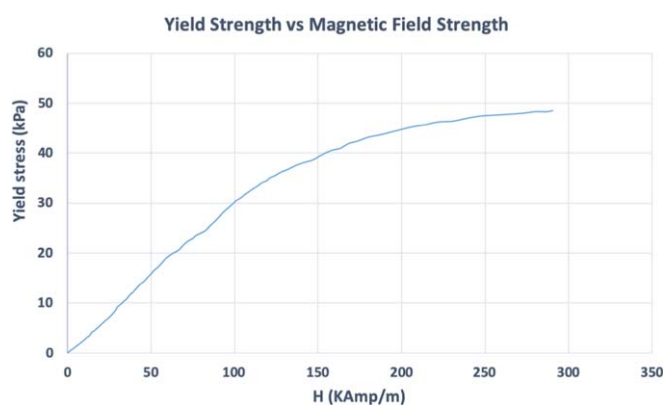


Figure 8. Typical magnetic properties of MRF 132DG by Lord corporation [28].

Table 2. Properties of MRF 132 DG.

Property	Value
Viscosity Pa-s @ 40 °C (104 °F)	0.112 ± 0.02
Density g/cm ³	2.95–3.15
Flash Point, °C (°F)	>150 (>302)
Magnetic field strength(H)	150–250 [kA/m]
Operating temperature °C (°F)	−40 to +130 (−40 to +266)

piston, cylinder and rod [27]. Non linear magnetic properties of low carbon steel are available in the COMSOL material library. Copper material was used to model a multi-turn coil with number of turns as 350. It was implemented as the magnetic intensity inducer and for the simplification it was represented as a lumped model.

Ampere's law was used to generate magnetic field in the model and constitutive relation used in MR fluid, Low carbon steel was non linear HB curve. Constitutive relation as in equation (15) was used in Ampere's law of coil and an air body.

Axial symmetry boundary condition was added in the MF module. Air boundary was used to insulate the model. Multiturn coil was used to represent solenoid. Variable current (I) was defined so as to give varying input current which will then generate current in coil. Simulation was run with a stationary study and parametric sweep using varying current from 0A, 0.5A, 1A, 1.5A, 2A, 2.5A for magneto static calculation. Hence magnetic field perpendicular to the coil was generated.

Magnetostatics equations are Maxwell's equations and it is given in equations (19) and (20)

$$\nabla \times H = J \quad (19)$$

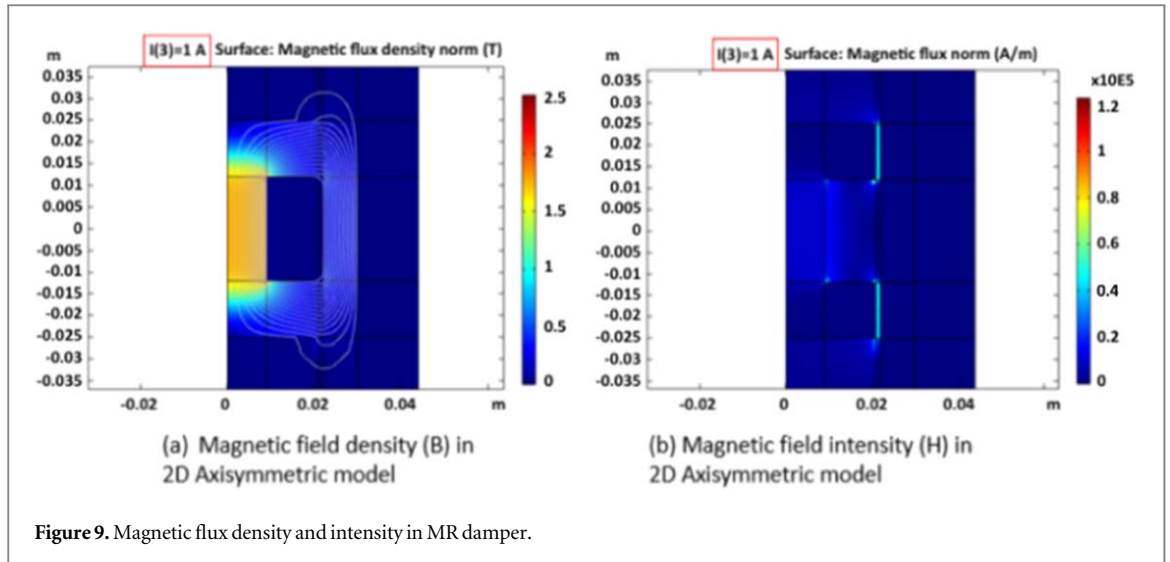


Figure 9. Magnetic flux density and intensity in MR damper.

$$B = f(|H|) \quad (20)$$

J is Current density which is given in equation (21)

$$J = \sigma E + J_e \quad (21)$$

which states that magnetic field was induced because of applied Current density J .

For quasistatic condition equation (21) was used

$$\nabla \times A = B \quad (22)$$

This was derived from Gauss's law which was equivalent to the statement that the field lines have neither a beginning nor an end: Each one either forms a closed loop and winds around forever without ever quite joining back up to itself exactly, or extends to infinity.

The constitutive relationship for Ampere's law between B and H for MR fluid and low carbon steel was defined as function of each other with the interpolation curve stated in equation (23).

$$B = \mu_o * \mu_r * H \quad (23)$$

J_e is external current density which is given to the coil and is given in equation (24)

$$J_e = \frac{NI}{A} \quad (24)$$

Magnetic insulation was provided in an FEA model using equation (25)

$$n \times A = 0 \quad (25)$$

Magnetostatic analysis was performed using FEA model in COMSOL.

5. Results and discussion

Magnetic circuit analysis was performed using FEM and magnetic flux density, magnetic flux intensity and related yield stress was obtained at the fluid flow gap of MR damper. Simulated results of magnetic flux density and intensity for 1A current was given in figures 9(a) and (b) and the plot of magnetic flux density with respect to varying input current from 0–3A shown in figure 10. It was observed that as the input current increases, the magnetic flux density and hence intensity increases proportionally. With FEM analysis, magnetic flux density of 0.61T and magnetic flux density of 122 kA/m was generated in the fluid gap. Table 3 includes variation of input current, magnetic flux density and magnetic flux intensity in fluid flow gap. Thus it is concluded from figure 8 that yield stress of 34 kPa is generated in fluid. Whereas using magnetic circuit theory magnetic flux density of 0.64T was generated and using equation (16) yield stress was calculated as 34 kPa. The difference of 4.8 percent between two results was due to non linear BH curve consideration in Finite element analysis over linear consideration of BH relation in magnetic circuit theory. It is concluded that the yield stress generated in fluid is below dynamic yield stress of 50 kPa of MRF 132 DG, hence viscosity of the fluid increases given in equations (17) and (18).

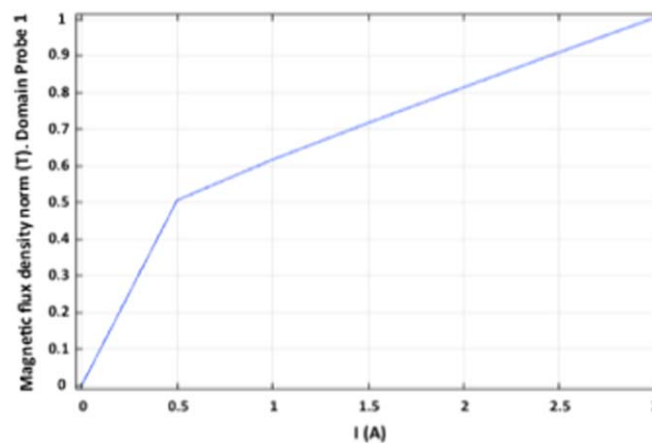


Figure 10. Magnetic flux density versus varying input current.

Table 3. Magnetic flux density and intensity variation with varying current.

I(A)	Magnetic flux density norm (T)	Magnetic field norm (A/m)
0.0000	0.00000	0.00000
0.5000	0.50642	1.0075E + 05
1.0000	0.61757	1.2286E + 05
1.5000	0.71743	1.4273E + 05
2.0000	0.81493	1.6212E + 05
2.5000	0.91051	1.8114E + 05
3.0000	1.00470	1.9988E + 05

6. Conclusion

An electromagnetic circuit simulation and magnetic circuit theory results comparison of monotube MR damper was proposed in this study. The FEA COMSOL software package helps in giving realistic the materials, the coil type, the coil's turn and the boundary conditions in order to achieve accurate results. study used in this FEA states that the magnetic flux density increases linearly with the increase in applied current. The permeability of low carbon steel is greater than that of MR fluid; hence, magnetic flux observed in piston material is more than that of MR fluid. It is concluded that magnetic flux density, intensity and yield stress in MR fluid of MR damper analyzed using FEA are validated using magnetic circuit theory.

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